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Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings

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Abstract

This study presents a method to adapt existing hydronic systems in buildings to take advantage of low temperature district heating (LTDH). Plate radiators connected to double string heating circuits were considered in an optimization procedure, based on supply and return temperatures, to obtain the required logarithmic mean temperature difference (LMTD) for a low temperature heating system. The results of the analysis are presented as the average reduction of LMTD over the heating season compared to the base case design conditions. Two scenarios were investigated based on the assumption of a likely cost reduction in the end users' energy bills of 1% for each 1 °C reduction of return and average supply and return temperatures. The results showed possible discounts of 14% and 16% respectively, due to more efficient operation of the radiators. These were achieved without any intervention in the thermal envelope or to the heating systems, through simply adjusting the temperatures according to demand and properly controlling the plate radiators with thermostatic radiator valves (TRVs).

Keywords: Low temperature district heating, hydraulic radiators, modelling, temperature optimization

Highlights

- Application of low operating temperatures to existing hydraulic radiators
- Method to investigate and plan the connection of existing buildings to low temperature district heating
- Investigation to calculate performance of hydraulic radiator element
- Method to optimize supply and return temperatures in low temperature district heating system

1 Introduction

In the EU households, heating for space heating (SH) and domestic hot water (DHW) consumes 79% of the total final energy use (192.5 Mtoe), representing one of the largest carbon emitting sectors of the economy [1][2]. As a consequence, decarbonizing the heat sector is being considered central to the EU energy policy to foster a carbon neutral society and achieve the reduction in the greenhouse emission of 40% and 80% by 2030 and 2050 respectively to the level of 1990 [3]–[5]. Currently, heat supply in buildings in the EU is mainly provided by individual heat sources installed in buildings or alternatively through district heating (DH) networks. The latter are widely used in Scandinavian, Eastern European countries and Russia. District heating offers high flexibility for the integration of renewable heat sources, though still faces the technical challenge of matching different heat sources' supply temperature and demand. Driven by the need to use low carbon heat sources, the current focus is to develop low temperature district heating systems, referred to as 4th generation district heating (4GDH) [6]. One key design parameter in the development of 4GDH is the reduction of supply and return temperatures from the current standard of 80/40 °C to load dependent temperatures with a target of 50/20 °C. As DH in general covers the demand for SH and DHW, the limit for the supply temperature of 50 °C is imposed to avoid health problems due to Legionnaires' disease in sanitary water [6], [7]. Recent studies show that buildings can be maintained at comfortable temperature levels with low supply temperatures for the majority of the heating season and using a 4GDH system with flexibility to adjusting the temperatures according to heat demand during extreme low outdoor temperatures. This would improve the overall efficiency of heat generation and reduce heat losses in the network [8]–[10]. Therefore, one of the issues in the implementation of low temperature district heating (LTDH) is the calculation of the optimal combination of supply and return temperature to operate the heating systems according to heat demand. In fact, reducing supply temperature to 50 °C poses few technical problems in regard to the capability of existing heating systems to guarantee the same thermal comfort. Commensurate with low-energy buildings, which use efficient heat emitters such as low-temperature radiators or underfloor heating, water supply temperatures of 50 °C or even lower would technically be adequate to meet SH demand all year round [11]–[13]. Hence, the challenge is to adapt the existing large building stock and the already installed hydronic heating systems for the applicability of LTDH, without any major design and construction intervention, yet adjusting water temperatures to heat demand.

1.1 Aim

The aim of the work presented in this paper was to develop a method to investigate and plan the introduction of LTDH to existing hydraulic radiator systems in existing buildings. The scope of this work was to express the heat demand as a function of logarithmic mean temperature difference (LMTD) between the water of the hydraulic radiator and the heated building zone. The results of the investigation are expressed as an average reduction in LMTD over the heating season compared to the design conditions. The needed LMTD can be reached by numerous combinations of supply and return temperatures to the radiator; these have different economic benefits and therefore an optimization process to define the best combination of supply and return temperatures is needed. Hence, two different scenarios for double string plate radiators were used to test the developed method and outline the strategy to connect existing buildings to LTDH.

1.2 Modelling performance of different types of heating elements for low temperature operation

Lower return temperatures are beneficial for DH technology, by reducing the network distribution losses and mass flow rates, as well as improving the efficiency of energy generation [14]–[17]; this is even more important for the LTDH concept, where return temperatures have to be cooled to almost indoor temperature. In mature DH markets such as in Denmark, Sweden and Finland, LTDH has been successfully applied and tested in real projects. Good results proved the concept in case of low-energy buildings [8], [18], [19] and further investigations have been carried out for existing buildings at different levels of refurbishment [20], [21]. However, none of these articles includes an optimization process, based on the economic value of lower supply and return temperatures for DH companies and end users, to define the optimal operating temperatures in the implementation of LTDH to existing buildings with radiator based heating systems. Hence, to correctly address the challenge of operating existing hydraulic radiators with low water supply temperatures, necessary considerations must be given both to the design of the heat emitting radiators (hardware) and the modelling analysis to optimize the performance.

1.2.1 Hardware part – type of heating systems

Hardware considerations include the different types of heating elements, the way they are operated and controlled in order to efficiently perform. Commonly, flat panel radiators are manufactured by combining up to three flat plates and incorporating fins to augment the heat transfer area [22], [23]; they can have a high or low profile. By far the most used hydraulic configuration for radiators is the double string system, consisting of two pipes, one for supply and one for return. Typically, hot water is supplied to the top of a radiator to let the water flow diagonally downwards and cool gradually before leaving from the opposite bottom corner [24]. Although low level panel radiators are used in some cases, especially if there are space restrictions, they can lead to slightly higher return temperatures compared to taller ones, due to the reduced height; hence particular attention is necessary during the selection of the element if low return temperatures have to be attained. Another possible hydraulic configuration for radiators is the one string system, characterized by only one pipe for both supply and return; the radiators are connected in a way that a fraction of the water flow in the main string runs through the radiator and exits back to the main string. The temperature though is gradually reduced as this enters to each successive radiator. This solution fosters the system to work with higher mass flow rates and lower temperature difference (ΔT). If carefully designed by increasing the size of each successive radiator [25], as reported in this study published by the Swedish DH association [26], return temperatures can be as low as in double string systems in typical DH networks. Nonetheless, as difficult to properly control, it is common to experience higher return temperatures and smaller ΔT in the substation, hence this reduced their attractiveness in comparison to double string systems, in particular when connected to district heating [27]. Similar to the radiators with single string hydraulic configuration, heat convectors lead to higher return temperatures due to high flow rate and low ΔT. They are characterized by heat transfer to the surrounding mainly by convection and the most common layout consists of a finned long tube, which generally follows the perimeter of exposed walls and/or windows [22]–[24], [28], [29]. These heating elements – likewise water radiators with single string layout – still can be found in existing buildings, but they are not recommended for DH in general and in particular not for LTDH applications, where return temperatures close to room temperatures have to be achieved. Central to hardware discussion is also the way radiator elements are controlled, typically by thermostatic radiator valves (TRVs). TVRs are passive water flow regulating devices that maintain set-point room temperature; this guarantees the required indoor comfort in an efficient way as well as the expected cooling of return temperatures. It also allows the heat output to modulate and compensate for emitters that can be over-dimensioned during some periods of the heating season [30]–[32]. However, it is quite common in real applications for TRVs to operate poorly and negatively affect the overall system efficiency. The work of Ziao et al. [33] found that in hydronic radiator systems, although TRVs were installed in almost all the systems surveyed, in 65% of the cases they were performing poorly, mostly due to occupants misuse, and generating thermal discomfort and wasted energy. Therefore it is important to limit the side effect of human behavior on the effectiveness of TRVs [34], as these have a decisive role in overall system efficiency and in the cooling of return temperatures. This was further highlighted by the investigations of Monetti et al. [35], Xu et al. [36] and McNamara [37] who showed that properly installed and controlled TRVs can lead to savings of 10%, 12.4% and 15% respectively, with relatively low-cost retrofitting investment and short payback periods.

1.2.2 Modelling part – calculation of heating demand of rooms and heating power of radiators

The thermal performance of existing hydraulic radiator systems operating at lower temperature should comply with current EU design practices and standards and computer modelling allows accurate prediction of water temperature profiles in the radiator and heating capacity [38], [39]. It is important that the emitters are correctly sized and operated to deliver the heat needed; thus the challenge is to outline the optimal temperature of supply and return to meet the heat demand. Hydronic systems are typically sized based on the worst case scenario of steady-state heat output that meets winter design conditions and do not consider sources of heat gains. This leads to over-sizing systems and guarantees a larger surface area, in the case of radiators, and a positive effect when lowering temperatures [14], [15], [21], [40]. Lauenburg [41] showed that heating systems sized for design temperatures only required full load during a short period when outdoor temperatures are very low, demonstrating that for most of the heating season consistently lower water supply temperatures can be appropriate to meet the heat demand. The reliability of software outputs is crucial because it provides a powerful tool for professionals at the time of investigating and foreseeing the use of low temperatures to existing hydraulic radiators. It is important to choose an adequate radiator element and correctly define the physical characteristics of the heating element, including control by TRV. For instance, the open-source EnergyPlus, one of the most used and powerful software for energy simulations, only gives the user the option of a 'hot water baseboard heater with radiation and convection' [42], [43]. This element has both radiative and convective components as with a radiator, but in reality is a convector. Therefore, the user can still perform accurate dynamic energy simulations for the building in analysis, but the accuracy could be affected if the focus of the investigation is specifically related to the cooling of the return temperatures in existing hydraulic radiator elements at time of lowering the operating temperatures of the system. From this perspective, the paper adds new knowledge by developing an alternative method to investigate and plan the application of LTDH to existing buildings, outlining an optimization strategy to define the best combination of supply and return temperatures to operate existing hydraulic radiators.

2 Methodology

2.1 Hardware part – type of heating system

The investigation related to the application of LTDH to existing buildings with a characterization of heating systems with respect to the type of heating loop and heating elements. The characterization mainly addressed the possibilities of operating the systems with low return temperatures. An example of a system with low return temperature is a double string system with panel radiator, whereas the examples of systems with high return temperature are:

1. single string with all type of heating elements
2. double string or single string with convectors

2.2 Modelling part – calculation of heating demand of rooms and heating power of radiators

The method used in the investigation is based on modelling in a number of steps and illustrated with a specific case as follows.

2.2.1 *Step a: calculation of part load duration curve*

This is to define the part load duration curves for each room of the building considered. The starting point was the characterization of the design conditions of the heating system: this was made for the case study by performing steady-state simulations to outline the design heat load for each room according to Danish standards [44], assuming no heat gains and the design winter temperature of -12 °C. Once the design conditions were defined, detailed dynamic simulations were performed to outline the realistic heat load distribution for an entire year using a weather file for Copenhagen based on a 20 year historical database; this allowed the specific part load duration curves to be obtained for each room on an hourly basis.

2.2.2 *Step b: calculation of the relationship between part load and logarithmic mean temperature difference of the hydraulic radiator elements*

This is to calculate for each room how the hydraulic radiators have to be operated to meet the heat demand outlined in *step a*. This was established for this study by associating to each part loads the specific LMTD for the specific radiator size of the room.

2.2.2.1 *Hydraulic radiator formulation*

The empirical formula used to evaluate radiator performance and the capacity of cooling the return water temperatures is based on analysis of the heat emitted as a function of the LMTD between water and room temperature. The general formula is described by Equation 1 [38], [39]:

$$\varphi = \left(\frac{LMTD}{LMTD_0}\right)^n \varphi_0 \tag{1}$$

where φ and φ_0 present the heating power at operating temperatures and design conditions (W), *LMTD* and $LMTD_0$ denote the logarithmic mean temperature difference between radiator and surroundings at the operating temperatures and design conditions (°C), whereas n is the radiator exponent and describes the exponential relationship between the mean temperature difference and the heat emitted from the radiator – 1.3 is the typical value for hydraulic radiators [12].

The logarithmic mean temperature distribution, included in the Danish standard [45], is expressed by Equation 2.

$$LMTD = \frac{T_S - T_R}{ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \tag{2}$$

where T_S is the supply temperature (°C), T_R the return temperature (°C) and T_i is the indoor operative temperature (°C).

2.2.3 Step c: calculation of the duration curve of logarithmic mean temperature difference

Given the hourly heat load duration curve in *step a* and the relation of part load and LMTD obtained in *step b*, in *step c* the duration curve of LMTD has to be calculated. The application of the method allows calculation of the LMTD duration curves for each room and all buildings in the analysis of an area in the process of being connected to LTDH. Within all the curves, the worst cases represented by the highest LMTD duration curves have to be carefully assessed and possibly excluded from the analysis. These cases may represent typical errors in radiator design, undersized systems or unheated rooms; therefore they need to be investigated separately and improved by reducing heating demand or increasing heating capacity of radiators in order to operate more efficiently and guarantee the expected cooling of return temperatures. However, this part is not included in the results as the case in this study is with one room and one building. The full application of the method will be part of a future project.

2.2.4 Step d: calculation of the optimal supply and return temperature to provide the necessary logarithmic mean temperature difference

Step d is the calculation of the optimal combination of supply and return temperatures to provide the necessary LMTD obtained from *step c*. The optimal combinations of supply and return temperatures have to be presented for all relevant LMTD. The goal of the optimization is to minimize the operating supply and return temperatures in order to assess the capability of existing hydraulic radiators to be operated with lower temperatures without any intervention to the building or to the heating system, in the prevision of being connected to LTDH. This was addressed by formulating the optimization problem based on the *objective function* and *constraints*. These vary according to the different scenarios investigated and each of them is illustrated in details in section 4.

3 Description of the case study building

3.1 Danish single family house

The method was tested by the use of a specific case based on a typical Danish single-family house from the 1930s, sited in Copenhagen. A model was created in the dynamic simulation software IDA-ICE [46] as presented in Fig.1. The software has been validated in accordance with standard DS/EN 15265, which describes dynamic simulation of energy performance of buildings [47], [48].

The building is made of red brick cavity walls, red tile roof and a basement. Typical of Danish buildings from 1930s, old windows and radiators have been replaced, as well as improvement to roof insulation. Table 1 shows the main properties of the house.

The presence of occupants and their use of equipment was modelled on weekly schedules. Compared to average Danish values for heat gains in domestic building environments [49], conservative values of 0.81 and 1.55 W/m^2 were assumed respectively for heat gains from occupants and equipment [50]. The natural ventilation was assumed to be fixed at 0.3 l/s per m^2 of floor area, which corresponds to the standard ventilation required in the Danish Building Code [46], and includes infiltration from opening of windows and doors in the winter time.

3.2 Example of hydraulic radiator return temperatures based on the radiator formula

A comparison was made between real measurements and the simulations' outputs to identify the capacity of IDA-ICE to correctly model the cooling of return temperatures. The analysis was performed considering the radiators installed in the single family house presented in section 3.1. The radiator formula is used as model for the heating element performance in the simulation program IDA-ICE. The house was examined and the size and type of radiators in all rooms was measured and checked; the number and the location of each radiator are shown in the plans of Fig. 1. In addition, indoor temperatures, heating system temperatures and heating consumption over the course of one month, between 10th March and 13th April 2015, were monitored and collected on an hourly basis. During the monitored period, the energy demand for SH and DHW was provided by a condensing natural gas boiler, placed together with a hot water tank of 110 litres in the basement. The building was switched to district heating during the following June, after the measurements in the house had been taken. The heating system consists of double string hydraulic radiators and electric floor heating is installed in both bathrooms. The existing radiators in the house were simulated using their correct dimensions, nominal design conditions, exact location, and a TRV was set for each of them. In order to accurately model the operating conditions of the hydronic system and achieve reliable results, the simulations were run using the real hourly weather data for the period in analysis; the recordings were obtained from measurements taken by the Danish Meteorological Institute, whereas the diffuse and direct solar radiation were collected at the nearby weather station of the Technical University of Denmark [52]. Also, the performance of the heating elements available in the software were evaluated by running the simulations using the supply temperature curve obtained from the measurements, and the simulated results for the return temperatures out of the radiators in selected rooms were compared to the measured ones on an hourly basis. The average supply temperatures in the period recorded for the SH demand was 45 °C and it was enough to guarantee the expected indoor comfort; the mean outdoor temperature was 5.3 °C and the lowest value registered was -2.5 °C.

The comparison between the IDA-ICE outputs and the real return temperatures collected from the radiators over 24 hours, using dedicated temperature sensors, is presented in Fig. 2 for two selected rooms. The importance of comparing the results over an interval of 24h was driven by the necessity of testing the accuracy of the software to reflect the influence that all the dynamic variables involved have on the performances of the radiators throughout a typical day. The results obtained show a good match between the simulations and the real measurements of the return temperatures for the period considered. The average return temperatures calculated by the software were 22.0 °C and 22.9 °C for the kitchen and hall respectively, whereas the average data collected were 22.4 °C and 22.5 °C. Therefore, the hydraulic radiator unit available in IDA-ICE provides robust results and can efficiently model the cooling of the return temperatures. It is also important to notice how the real data collected shows how existing hydraulic radiators can be operated with low temperatures and connected to LTDH, guaranteeing the expected indoor comfort.

4 Results and discussion

4.1 Hardware part – type of heating system

Two scenarios were investigated to test the application of the method developed considering a heating system with double string plate radiators. For both of them it was assumed a direct connection to the heating systems without any heat exchanger. However, the performed analysis can also include the presence of heat exchangers by accounting for their efficiency.

4.2 Modelling part – calculation of heating demand of rooms and heating power of radiators in double string system

The developed method was intended to be applied to an area in the process of being connected to DH and it was supposed that the building chosen, in the scenario with double string with plate radiators, was representative of the urban area in analysis. The application of the method was tried on one selected room, the hall of Fig. 1, and the results for the four steps described in the methodology are presented as follows.

4.2.1 Step a: calculation of part load duration curve

According to the steady-state simulations based on the Danish standard [44], the design heat load calculated for the specific room was 884 W. Also, the dynamic simulation outputs are presented in Fig. 3 and depict the part load duration curve for the room in analysis on an hourly basis for the entire year.

4.2.2 Step b: calculation of the relationship between part load and logarithmic mean temperature difference of the hydraulic radiator elements

The results for *step b* presented in Fig. 4 illustrate the relationship between each part load and the specific LMTD, expressing how the radiators need to be operated. It was assumed that the radiators in the double string configuration at design conditions were operated with supply and return temperatures of 80/40 °C. In addition, to correctly perform the calculations of LMTD per each part load using Equation 1, n was assumed to be 1.3, φ_0 was the design heat load of 884 W, whereas $LMTD_0$ was obtained from Equation 2 using the design temperatures of 80/40 °C and set indoor temperatures of 20 °C.

4.2.3 *Step c: calculation of the duration curve of logarithmic mean temperature difference*

The part load duration curve presented in Fig. 3a and the general relation between the part load and LMTD in Fig. 3b allowed calculation of the duration curve of LMTD on an hourly basis as described in Fig. 3c. The graphical combination of the curves of Fig. 3, 4 and 5 provides a tool to clearly identify the number of hours per each range of part load or per each degree °C difference of LMTD, hence the exact amount of energy necessary to guarantee the expected indoor comfort through the radiators. These curves and in particular the curve of fig. 3c can be used to compare different buildings and different rooms, helping to define the conditions and the boundaries to be investigated for implementing LTDH in an urban area.

4.2.4 *Step d: calculation of the optimal supply and return temperature to provide the necessary logarithmic mean temperature difference*

Two different scenarios, A and B, were investigated and consequently the formulation of the optimization problem followed two different strategies. Both scenarios assess the impact that different DH markets have on the definition of the optimal combination of supply and return temperatures to operate the same hydraulic radiators. The results are presented in Fig. 6 and 8 and illustrate on one hand the technical and economic factors affecting the selection of the optimal temperatures; on the other hand, to which extent temperatures can be lowered without any intervention to the thermal envelop of the building or to the heating system.

4.2.4.1 *Scenario A: typical Danish DH network*

In Danish DH market more than 70% of heat is produced taking advantage of CHP technology and the price of heat unit only includes all the necessary costs related to supply heating, as DH companies are not allowed to make any profits [53]. Also, as lower supply and return temperatures reduces the costs associated to heat generation and distribution losses, typically DH companies incentivize their customers through *motivation tariffs* to reduce their temperatures in exchange of a discount in their energy bills. These are normally customized according to the specific characteristics of DH systems and relative end-users connected. From this perspective, Scenario A was designed assuming the figures of a real motivation tariff related to an existing Danish DH company [54], where the heat generation is based on a biomass boiler with flue gas condenser. For the considered DH network, the company is able to guarantee to end users a discount of 1% in their energy bill (up to a maximum of 20%) for each °C lower in their return temperatures compared to the reference DH yearly average return temperature. The assumed reference average yearly supply and return temperatures were 80/40 °C as typical for Danish DH networks. The discount offered is compensated by the savings made by the DH company due to the lower supply and return temperatures. In fact, at actual market conditions, according to their cost analysis [54], lower return temperatures have higher economic value due to the savings in buying energy at the generation point, compared to the reduction in the distribution heat losses due to lower supply and return temperatures. Hence, the strategy of the optimization was based on the minimization of the supply and return temperatures of Equation 2 set equal to the specific LMTD for each value of the duration curve presented in Fig. 6.

The strategy followed three different paths clearly delimited by the breaking points related to LMTD of 14 °C and 23 °C corresponding to the change in the gradient of the optimized supply and return curves calculated – i.e. Fig. 3d. The objective functions and relative constraints are presented for all specific LMTD as follows:

i. *For LMTD < 14 °C:*

$$\text{minimize } (T_R), \, for \; LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \tag{3}$$

Subject to:

$$T_S = 50 \text{ °C} \tag{4}$$

$$\dot{m} \leq \dot{m}_0 \tag{5}$$

ii. *For 14 °C ≤ LMTD ≤ 23 °C:*

$$\text{minimize } (T_S), \, for \; LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \tag{6}$$

Subject to:

$$T_R = 25 \text{ °C} \tag{7}$$

$$\dot{m} \leq \dot{m}_0 \tag{8}$$

iii. *For LMTD > 23 °C*

$$\text{minimize } (T_R), for\ LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \tag{9}$$

Subject to:

$$T_S = 80\ °\text{C} \tag{10}$$

$$\dot{m} \leq \dot{m}_0 \tag{11}$$

where T_S is the supply temperature (°C), T_R is the return temperature (°C), T_i is the indoor operative temperature (°C) – fixed at 20 °C, $\dot{m}$ is the mass flow rate associated to the generic combination of T_S and T_R (kg/h) and $\dot{m}_0$ is the max mass flow rate at design conditions (kg/h).

The max mass flow rate of 19 kg/h was obtained from Equation 12:

$$\varphi_0 = 3600 \cdot \dot{m}_0 \cdot c_p \cdot (T_{S\_0} - T_{R\_0}) \tag{12}$$

where φ_0 presents the nominal heating power at design conditions (W), $\dot{m}_0$ is the max mass flow rate (kg/h), T_{S_0} is the supply temperature at design conditions (°C), T_{R_0} is the return temperature at design conditions (°C) and c_p is the specific heat capacity of water (J/kg °C).

In the resolution of the optimization problem all the combinations of temperatures fulfilled the constraints' criteria. The lower supply temperature limit of 50 °C is imposed by national standards to avoid the risk of Legionnaires' disease in DHW [6], [7] and it was assumed that supply and return temperatures of 50/20 °C out of the heating season were enough to meet the DHW demand. The upper limit of 80 °C instead was assumed as the maximum inlet temperature according to the specific DH network. In addition, according to normal operation practices of radiators, a target return temperature of 25 °C was set as a realistic value given the indoor room temperature of 20 °C. This was in fact one of the constraints in the minimization of the supply temperatures for all LMTD included in the range between 14 °C and 23 °C. These two points, corresponding to the change in the gradient of the optimized curves proposed, illustrate that for LMTD lower than 14 °C, due to the combination of low heat demand and low mass flow rates, the return temperatures were always below the target temperature of 25 °C and supply temperatures could be set as low as 50 °C; contrarily, for a LMTD higher than 23 °C the combination of high heat loads and high mass flow rates led to return temperatures always higher than 25 °C and supply temperatures were fixed to 80 °C to guarantee the expected indoor comfort and avoid unnecessary high return temperatures. Comparing to other studies where LTDH concept was applied to low-energy buildings [8], [18], [19] and to existing buildings at different levels of refurbishment [20], [21], the outcomes presented in Fig. 6 show for this scenario that existing heating system based on double string radiators, if properly controlled, can be operated more efficiently and achieve low return temperatures for each LMTD without any intervention to the building, but simply adjusting temperatures to heat demand. Thus, the calculated combination of supply and return temperatures can be used by the district heating company to efficiently operate the network, controlling the supply temperatures according to the optimal level. To this extent, Fig. 7 presents the relationship between the optimized supply/return and outdoor temperatures. This outlines the strategy to be followed by the DH company to meet the heat demand for the hypothesized urban area, assuming that the building and the room chosen were representative.

The curves were calculated by finding the hourly peak load from the heat load profile of Fig. 3 for each °C of the outdoor temperatures and associating for specific LMTD the optimal temperature combination from the results presented in Fig. 6. The use of hourly peak loads for each °C of outdoor temperature is a conservative choice that guarantees the temperatures would deliver the heat demand in all conditions. Different approaches considering more realistic peak values, based on daily, 12 or 6 hour averages, are possible, but the evaluation has to be linked to the characteristic of the network in analysis and its capacity to adjust temperatures and pressures to the customers connected and to the use of weather forecasts. Therefore, operating the DH network and the radiators as proposed would lead to implementing lower temperatures in the area and result in a possible discount of 14% in end users' energy bill according to the assumed *motivation tariff*, due to the lower return temperatures achievable compare to the reference yearly average of 40 °C assumed.

4.2.4.2 Scenario B: future DH market

In the second scenario, the importance of integration of renewable and low carbon heat sources for future DH markets was evaluated. Lowering supply temperatures compared to the present market would increase the economic benefit for DH companies. Furthermore, lower supply temperatures allow heat sources such as heat pumps to operate more efficiently by increasing the COP, to recover waste heat, to connect solar plants with seasonal storage and to reduce the impact of distribution losses [5]. These future conditions were integrated in the analysis of this scenario, by assuming a *motivation tariff* where the DH company would guarantee a discount of 1% to end users in their energy bill (up to a maximum of 20%) for each °C lower in the average of supply and return temperatures compared to the reference DH average supply and return. This was assumed as 80/40 °C for this case study. Therefore, the key element of the optimization was expressed as the minimization of the average of supply and return temperatures of Equation 2 set equal to the specific *LMTD* for each value of the duration curve defined in Fig. 5. The objective function and constraints are presented as follows:

i. *For all LMTD:*

$$\text{minimize } \left(Average\ (T_S; T_R)\right), for\ LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \tag{13}$$

Subject to:

$$50°\text{C} \le T_S \le 80\ °\text{C} \tag{14}$$

$$\dot{m} \le \dot{m}_0 \tag{15}$$

For this scenario the indoor temperature T_i was set at 20 °C and max mass flow rate $\dot{m}_0$ from equation 12 was 19 kg/h. Each combination of supply and return temperatures fulfilled the constraints' criteria for hydraulic and supply temperature limits. As presented in Fig. 8, even in this case, well-controlled double string radiators can achieve low return temperatures, without any intervention to the thermal envelop of the building.

However, compared to scenario A, the outcomes illustrate that the optimal strategy to operate the radiators resulted in a reduction of the supply temperatures and an increased return temperature profile for each LMTD. This was related to the higher economic value associated to the supply temperatures in this scenario. A critical analysis of the curves presented in Fig. 6 and 8 shows for LMTD up to 14°C the optimal supply and return temperatures are identical for both cases; above that value the curves show the higher the supply temperatures the lower the return ones for each LMTD. This clearly indicates the compromise to decide whether and to which extent lowering supply and return temperatures is strictly related to the economic benefit that those have for the specific DH system in analysis. To this extent, the strategy to operate the DH network in this scenario and deliver the heat demand in the area by controlling the supply temperatures according to the optimal level is described in Fig. 9.

The curves show the relationship between the optimal supply and return temperatures linked to the hourly peak load associated to each 1 °C of outdoor temperature as described in section 4.2.4.1. Hence, operating the DH network and the radiators as proposed in Fig. 8 and 9 would define the strategy to implement LTDH in the area. In fact, as presented in study [8], LTDH is described as a system operating with supply temperature of 50-55 °C and return of 25-30 °C with the capability of increasing supply to 60–70 °C and return of 40 °C when necessary according to heat demand. Hence, the new operation of the heating system would guarantee to end users a discount of 16% in their energy bills according to the assumed *motivation tariff* due to lower average supply and return temperatures compared to the reference scenario. The results for the two scenarios, comparing the possible cost savings and average supply and return temperatures achievable, are presented in Table 3.

5 Conclusion

The developed methodology was used to investigate and plan the application of LTDH to hydraulic radiators in existing buildings. The results related to the double string scenarios showed the optimal operation of the existing plate radiators, properly controlled through TRVs and DH network, by adjusting the supply temperatures to the optimal level, achieved low return temperatures. This would allow existing buildings to be connected to LTDH without any intervention in the thermal envelope, through simply adjusting the temperatures according to demand, and obtain cost savings in the end users' energy bills. The strategy proposed for both scenarios A and B illustrated that a possible discount of 14% and 16% respectively could be achieved in annual energy bills. Furthermore, the design curves suggest the strategy to be followed for lowering supply and return temperatures has to be related to the economic impact those have in the DH network in analysis.

Due to the promising results obtained the focus is now to expand the investigation by implementing it in a real DH case study. Finally, it is central in the discussion to stress the importance of having well-controlled hydraulic radiators and limiting the impact of occupants misuse of equipment in order to efficiently operate the heating system and reach the expected cooling of return temperatures.

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List of Tables

Table 1: List of symbols and acronyms

List of symbols and acronyms	
DH	District heating
LTDH	Low-temperature district heating
LMTD	Logarithmic mean temperature difference (°C)
$LMTD_0$	Logarithmic mean temperature difference at design condition (°C)
ΔT	Delta T between supply and return temperature
TRV	Thermostatic radiator valve
SH	Space heating
DHW	Domestic hot water

φ	Heating power at operating temperatures (W)
φ_0	Nominal heating power at design conditions (W)
n	Radiator exponent
$\dot{m}$	Mass flow rate (kg/h)
$\dot{m}_0$	Max mass flow rate (kg/h)
c_p	Specific heat capacity of water (J/kg °C)
T_S	Supply temperature (°C)
T_{S_0}	Supply temperature at design conditions (°C)
T_R	Return temperature (°C)
T_{R_0}	Return temperature at design conditions (°C)

Table 2: Key data and construction elements

General parameters	
Number of occupants	2
Total floor area /basement area (m^2)	320/118
Heated part of basement [m^2]	47
Annual heating consumption [MWh]	20
Design winter temperature (°C)	-12
Building construction elements	**U-value (W/m^2K)**
External wall – insulated cavity brick wall	0.78
Roof -Tiles, wood beams and insulation	0.15

Windows – 2 pane energy efficient glazing	1.55

Table 3: Cost savings for optimized operations of double string radiators

		Double string	
	Reference DH scenario	**Scenario A**	**Scenario B**
Average return temperature (°C)	40	26	32
Average supply temperature (°C)	80	79	56
End-users energy bills’ savings (%)	-	14	16

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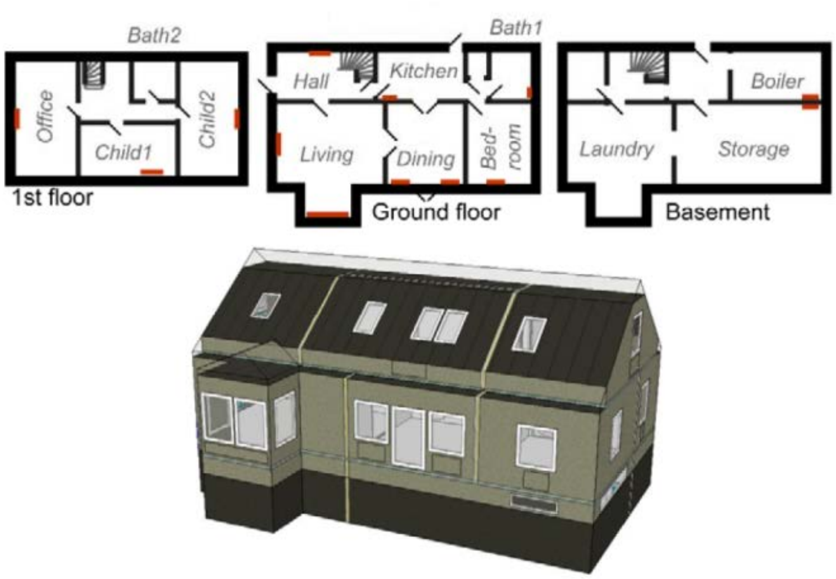


Fig. 1: Floor plans, radiators (in red) and IDA-ICE model [46]

Fig.2: Kitchen and Hall radiators' temperature comparison

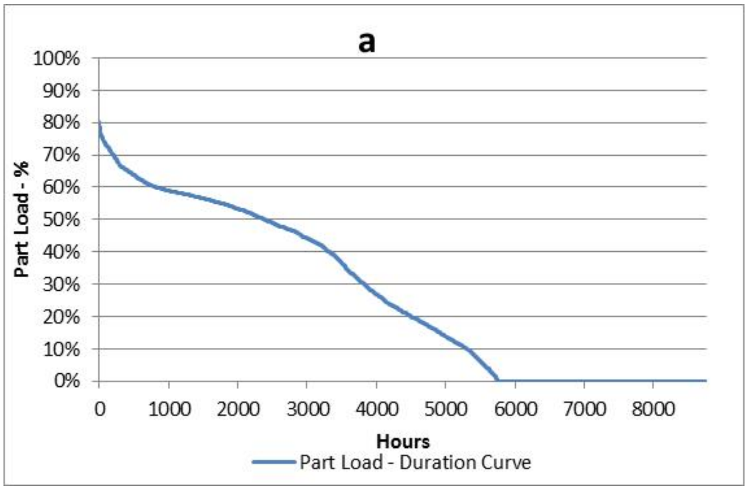


Fig. 3: Part load duration curve

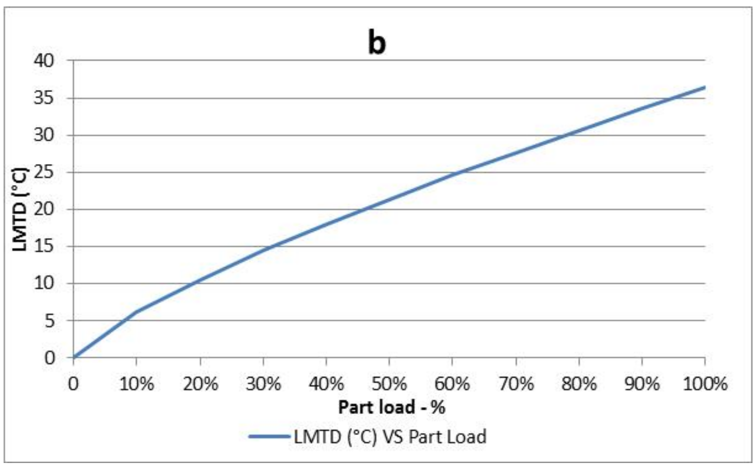


Fig. 4: *LMTD* VS Part load

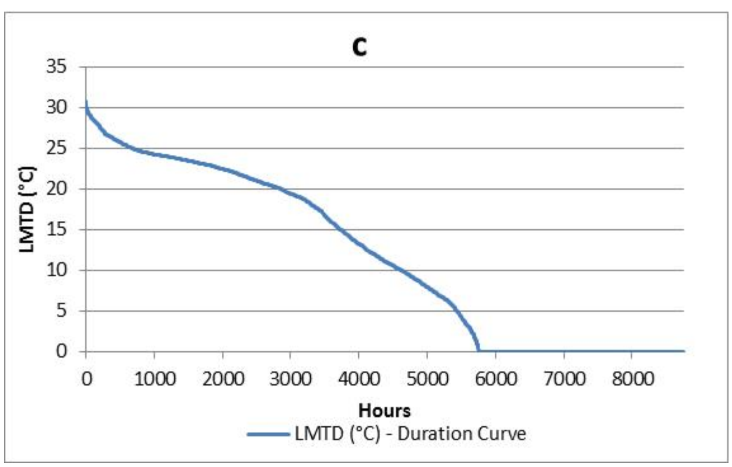


Fig. 5: *LMTD* duration curve

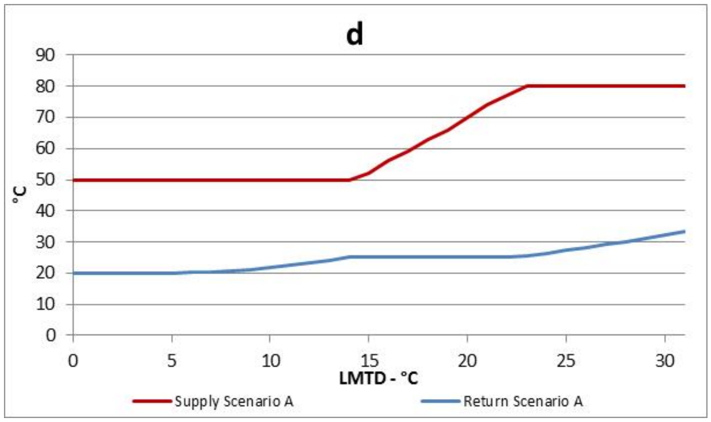


Fig. 6: Scenario A supply and return temperatures: optimization results

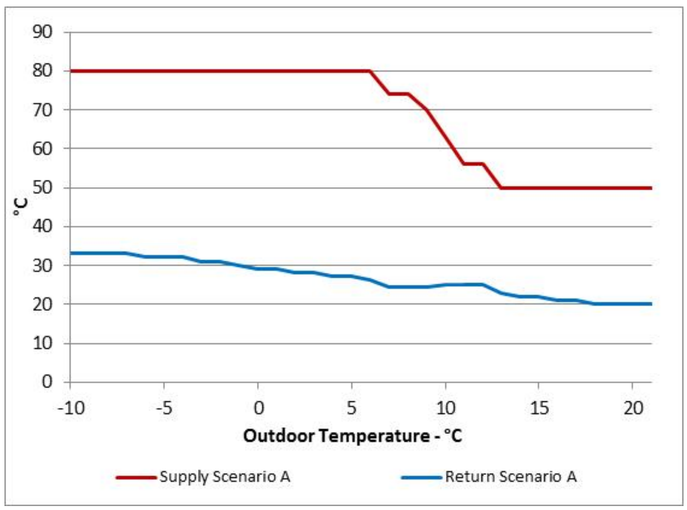
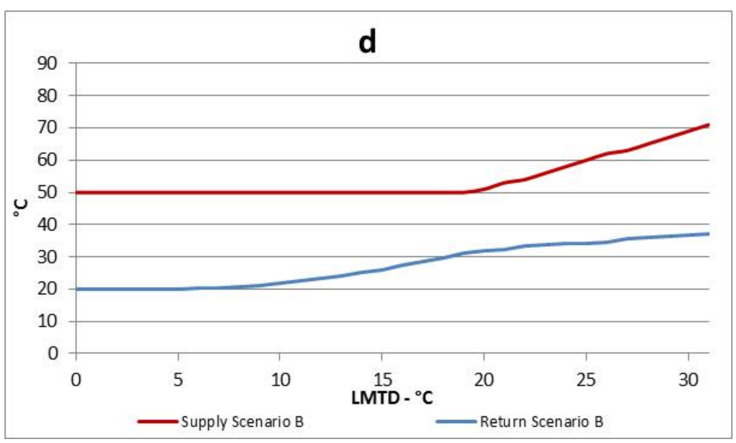


Fig. 7: Scenario A: relation between optimized supply/return and outside temperatures



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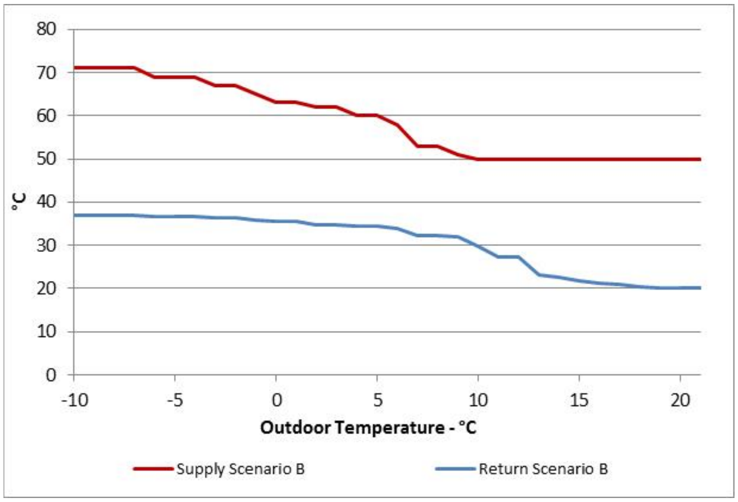

Fig. 9: Scenario B relation between optimized supply/return and outside temperatures